Deep Space 3 metrology system

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ABSTRACT

A metrology subsystem on board the Deep Space 3, a separated spacecraft interferometer mission, is used to determine stellar fringe delay jitter, delay rate, and initial delay. The subsystem implements two capabilities: linear metrology for optical pathlength determination and angular metrology needed to determine the configuration and orientation of the spacecraft constellation. Frequency modulated metrology concept is used to implement high-precision (5 nm) interferometric linear measurements over large target ranges (1 km). System is made angle sensitive by using an articulated flat mirror at the target.

Keywords: space-based stellar interferometry, separated spacecraft interferometer, interferometric metrology, frequency modulated metrology

1. INTRODUCTION

Deep Space 3 (DS3) separated spacecraft interferometermission is a technology validation mission for future space-based stellar interferometers. A key capability for any interferometrymission is the ability to measure and control optical path lengths with nanometer precision.

Laser metrology gauges are almost invariably used to implement the required high-resolution metrology systems. At JPL laser heterodyne interferometers are used as metrology gauges for a number of ground-based stellar interferometers and testbeds for space interferometer structures. Separated spacecraft missions, however, present an additional challenges of having to perform high precision metrology over long spacecraft separations. Deep Space 3 is currently baselined to operate at the spacecraft separation of 100 meters to 1 kilometer. Large target range coupled with small optics size due to size and weight limitations of a space-based mission results in the round-trip optical metrology loss of 25 dB. This renders a conventional heterodyne interferometer completely inoperable, because self-interference, a well known heterodyne interferometer "noise" source[1, 2], becomes comparable to the useful range-related signal. To address this issue on DS3 we plan to demonstrate a concept of frequency modulated metrology in which the self-interference should be suppressed by 4 to 5 orders of magnitude.

Another significant challenge for a separated spacecraft mission is the precise determination of the spacecraft constellation and its orientation with the respect to the starlight vector. These quantities must be known to estimate the external delay and delay rate; otherwise the fringe search time becomes prohibitively long. This capability is achieved by using a combination of a science star startracker and angular metrology. Angular metrology is implemented by replacing a usual retroreflector in a linear metrology system with an articulated flat mirror mounted on the target surface. As a result, the metrology system becomes sensitive to the orientation of the target, a siderostat in this case, and enables us to obtain enough information to solve for the astrometric angle between the baseline and the direction to the star.

2. FUNCTIONS AND REQUIREMENTS

The science observable of the DS3 mission is the visibility magnitude of the starlight fringe[3]. The DS3 metrology subsystem functions as a sensor that enables the starlight subsystem to find the starlight fringe and accurately measure its visibility. A conceptual schematic illustrating the quantities relevant to the performance of the metrology subsystem are shown in Figure 2.1.

Light from the science star is reflected by siderostat mirrors on the two collector spacecraft into the beam combiner on the combiner spacecraft. Key markers defining the optical path of the starlight are fiducial points P_1, P_2 and P_3. P_1 and P_2 mark

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the points where the light from the star is sampled by the interferometer and therefore define the baseline, B. Point P_3 marks the point where the two starlight paths are combined at the starlight beamsplitter.

The optical pathlength difference (OPD) between the internal optical pathlengths OPL1 (P_1 to P_3) and OPL2 (P_2 to P_3) is the Internal Delay and the path mismatch incurred by the starlight before it enters the interferometer is the External Delay=Bcos(θ). To form and observe starlight fringes, the overall Delay, consisting of the internal and external portions, must be measured, nulled, and kept nulled for the duration of the fringe visibility measurement. Disturbances and unknowns impacting the Delay can be classified into three categories: delay jitter, delay rate, and static delay.

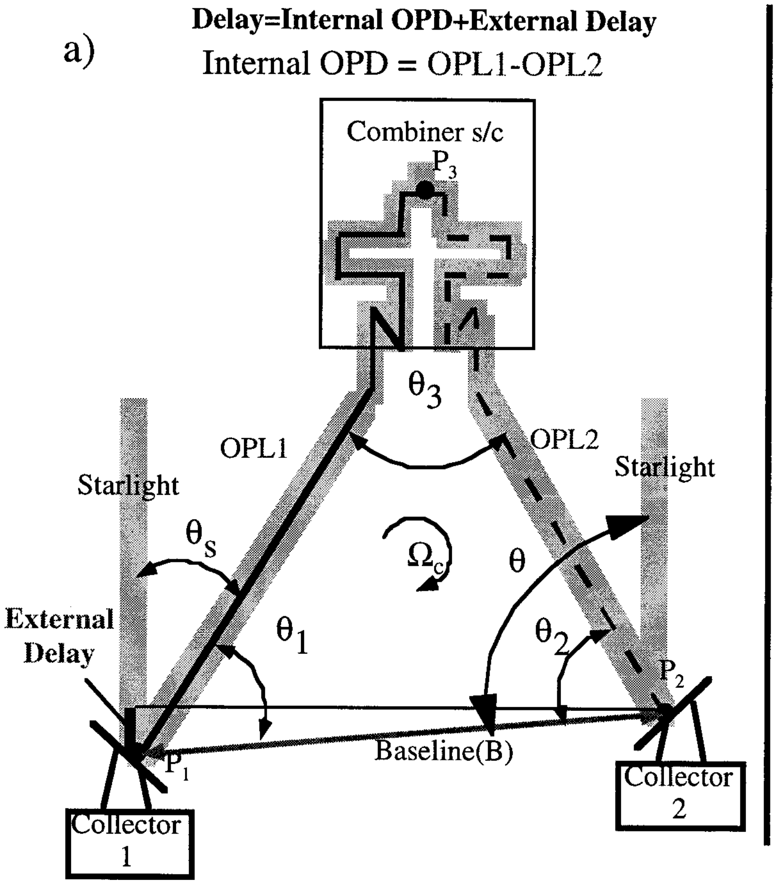

Figure 2.1. Functions and measurements definitions of the DS3 Metrology Subsystem

Delay jitter results from optical and mechanical instabilities in the dynamic relative separations between the three optical fiducial points. Once these are measured the three fiducial points form an optical truss triangle shown in Figure 2.1.b The truss is "rigid" in a sense that deviations from its original shape are detected by the relative metrology.

The uncertainty in the initial shape of the triangle and its orientation relative to the starlight direction, brought about by the limited resolution of the Autonomous Formation Flying(AFF) sensor[3], results in the prohibitively large unknown component in the initial delay. The metrology system needs to narrow this uncertainty down to 2 millimeters so that the starlight subsystem can perform a fringe search in a reasonable amount of time.

The rotation of the overall triangle(Ω_c) in the plane defined by the three spacecraft leads to a fringe delay rate which needs to be measured and compensated by the starlight subsystem during the fringe integration time.

We have identified a number of possible implementation approaches for a DS3 metrology subsystem and currently are planning a hybrid metrology system consisting of linear metrology and angular metrology components.

Delay jitter is measured with a linear metrology covering the two internal pathlengths, OPL1 and OPL2 shown in Fig. 2.1. The delay rate is obtained from combination of the linear metrology measurements between the three spacecraft(OPL1, OPL2, and B) and the measurement of the starlight angle, θ_s. The initial delay is estimated from the angular measurements θ_s, θ_1, θ_2, and θ_3. The implementation of the metrology system described in this paper is the baseline approach, but other approaches are still being considered.

3. LINEAR METROLOGY

Laser metrology gauges are a standard method for implementation of pathlength control in stellar interferometers. We plan to use gauges similar to those baselined for Space Interferometry Mission[4, 5]. The gauge is a heterodyne interferometer consisting of the following fiber coupled components: metrology source, beam launcher, and phase detection/control electronics, Fig. 3.1.

A dominant noise source in the heterodyne interferometers is the "self-interference" that results from imperfect routing of optical beams[1, 2]. Figure 3.1 illustrates the problem. Ideally, we would have only two signals at the photodetector PD_S, but in reality unwanted signals leak through onto it. The self-interference terms are usually on the order of a few percent of the desired signal. The problem for DS-3 is that the combiner-to-collector measurement path introduces a very high optical power loss into the measurement path. This loss reduces the desired signal, but does not attenuate some of the self-interference terms, thereby increasing the relative weight of the self-interference.

Power Loss Estimate and Metrology Beam Parameters

An output of a single mode optical fiber used to feed the beamlauncher is well approximated by a Gaussian beam and therefore a reasonable estimate of the power loss due to propagation between the spacecraft can be obtained by using Gaussian beam propagators. Clear aperture diameter allotted to the metrology beam is to D=2cm[3]. To minimize diffraction and power loss effects the Gaussian beam waist radius should be set at about w_o=1/3D. The resulting beam parameters are shown in Table 3.1. The 2 cm reflector at the collector siderostat intercepts only a small central portion of the beam and therefore the return beam is better approximated by a top hat beam. The overall round-trip loss is -25 dB or 0.3% of the power is returned to the signal photodetector. Because heterodyne interferometer uses synchronous detection the power loss of 25 dB leads to the signal reduction to $\sqrt{3E-3} = 0.05$. The self-interferencesignal is also on the order of a few percent and therefore this could lead to the self-interferencesignals being roughly equal to the desired signal. On the other hand, to have measurements resolution of 5 nm the self-interferenceterm must be kept under 2.4% of the desired signal. To avoid the problem created by polarization leakage and amplified by the high loss, we need to suppress the detrimental self-interference signal relative to the desired range-related signal. A concept for direct self-interferencesuppression by frequency modulation of the laser has been proposed[6] and is currently baselined for DS3 metrology subsystem.

Table 3.1. Metrology beam parameters and optical power losses

Parameter	Symbol/Relationship	Value
Clear aperture diameter at combiner	D_o	20 mm
Gaussian beam parameters (λ=1.32 μm)		
Gaussian beam waist radius(1/e^2 power)	w_o=1/3D	6.3 mm
Reileigh range	$z_0 = \pi w_0^2/\lambda$	106 m
Divergence angle (half-angle)	$\theta_d = \lambda/\pi w_0$	63 urad =13 asec
Gaussian beam radius		
at 1 km	w(1km)	63 mm
at 100 m	w(100m)	9.1 mm
Reflecting aperture diameter at target	d= D_o	20 mm
Power Loss at 1 km		
Beam diameter of the returning beam at the combiner (Top hat beam propagator)	D_R=1.22(λ/d)L	80 mm with λ=1.32 μm,
Downstream power throughput (from combiner to collector)	$\eta_d = 1 - \exp\left(-\frac{1}{2}\frac{d^2}{w^2}\right)$	~0.05 (-13 dB)
Return power throughput (from collector to combiner)	$\eta_{up}=(D_R/D_o)^2$	~0.06 (-12 dB)
Total power loss (throughput)	$\eta_T= \eta_d\, \eta_{up}$	~0.003 (-25 dB)

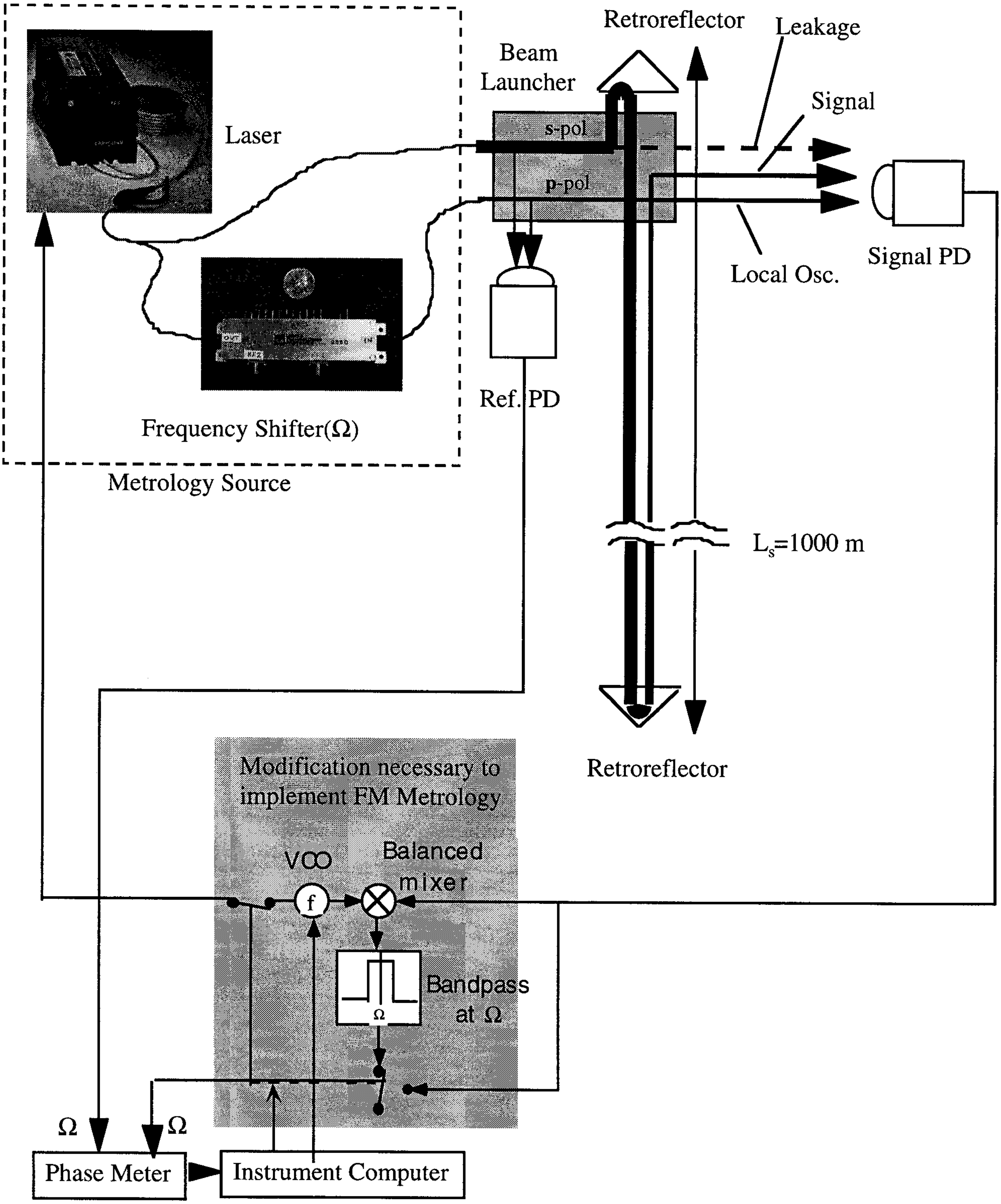

Figure 3.1. DS3 linear metrology concept.

Frequency Modulated Metrology

The metrology gauge proposed for DS3 is identical to a classical heterodyne interferometer except for an electronic addition/modification shown in a shaded box in Figure 3.1. A voltage controlled oscillator(VCO) operating at frequency f drives the fast frequency modulation input of the laser resulting in frequency modulation of amplitude $\Delta\nu$. For a description of the laser see ref.[7].

Time varying optical frequency $\nu(t) = \nu_0 + i\Delta\nu\cos(2\pi ft)$ leads to phase modulation of the heterodyne signal(S_s) coming out of the photodetector:

$$S_S \approx \cos\left(2\pi\Omega t + \phi_{L,\lambda} + m_S \cos(2\pi ft)\right) \tag{3.1}$$

where $\phi_{L,\lambda} = \frac{4\pi}{c}\nu_0 L$ - desired interferometric phase

L- difference in distance traveled by s- and p- polarizations.

$m_S \propto \frac{4\pi}{c}\Delta\nu L$ - modulation index

λ-optical wavelength, c-speed of light

The modulation index, and therefore the sidebands amplitudes, depends on the amplitude of frequency modulation($\Delta\nu$) and the optical pathlength difference between the two fields generating the heterodyne signal, see Fig. 3.2. For example, coming out of the photodetector, the first sideband at Ω+f will have the following form:

$$S_{sm} \propto J_1\left(\frac{4\pi}{c}\Delta\nu L\right)\cos\left(2\pi\Omega t + 4\pi\frac{L}{\lambda}\right) \tag{3.2}$$

For DS-3 the range-related signal pathlength difference(L)is on the order of 100-1000 m. On the other hand, the self-interference signal sees a pathlength difference(L_{SI}) which can be arranged to be at most a few centimeters[b]. We can therefore arrange it so that the range-related signal will have significant sidebands (J_1~0.6 for first harmonic of modulation frequency), whereas the corresponding sidebands of the self-interference signal will be much smaller (by a factor of $\approx L_{SI}/2L \approx 6\text{cm}/2\text{km} = 3E-5$). Consequently, we can significantly reduce the relative amplitude of the self-interference signal by using the sidebands, and not the fundamental, for subsequent phase measurement, see Fig. 3.2.

The pathlength-dependent amplitude will require tuning of the modulation frequency amplitude if the spacecraft separation changes by a significant fraction. On the other hand, it enables "absolute" optical metrology. This addition to the system's capability is being explored.

In summary, the DS3 linear metrology is based on heterodyne interferometer gauges implemented with a frequency modulated laser source. Frequency modulation is used to suppress high levels of self-interference induced by high optical power losses in the signal arm.

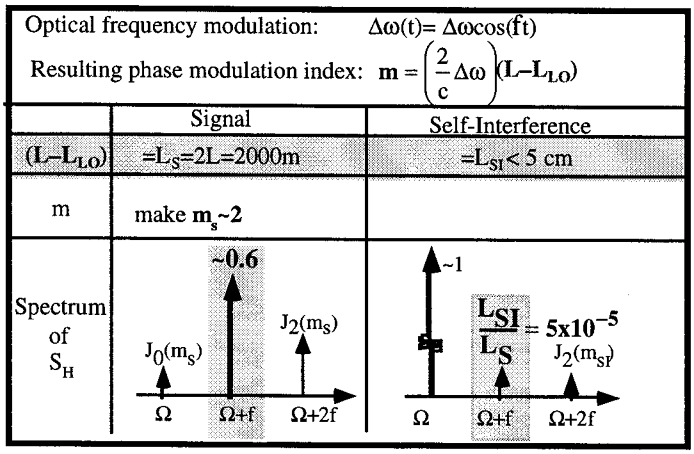

Figure 3.2. Illustration of the self-interference suppression by frequency modulation. For a more rigorous discussion see ref.[6]

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[b] Distance L_{SI} accounts for potential length mismatch between the two optical fibers feeding the beamlauncher and for extra distance travelled by the light backscattered by imperfectly coated beamlauncher optics.

4. ANGULAR METROLOGY

Purely linear metrology between the spacecraft is not enough to determine the initial delay or the delay rate, because it gives no information on the orientation of the interferometer constellation, i.e. the baseline vector, relative to the direction to the star. We have evaluated and continue to evaluate several methods of determining the orientation of the baseline vector in inertial space. The following presents our currently baselined concept[8].

For purposes of discussion, constellation rotation can be thought of as an angular drift of the star relative to a fixed interferometer constellation. Figure 4.1 illustrates the situation. Assume that the star has been acquired by the annular startracker in the starlight subsystem[3]. As the star drifts in the sky through an angle ϕ, annular startracker will sense the displacement of its image in the focal plane and will issue a command to the collector siderostat to compensate for star motion[8]. Provided this pointing loop is closed, we can determine the starlight angle and its evolution by monitoring the angle between the siderostat and boresight of the annular startracker, θ_{sd}. Once the starlight angle, θ_s, and the shape of the constellation triangle are known we can determine the baseline angle, θ (see Fig. 2.1). Basically, the annular strartracker uses the science star as the guide star and the metrology is used to fix/determine the pointing of the internal starlight path seen by the startracker. The implementation of the algorithm and most of the hardware mentioned above belong in the starlight subsystem and are summarized here to justify the need for angular metrology and to define relevant variables. For more detailed discussion of the starlight subsystem see ref.[3]. The requirements levied on the metrology system by this implementation of the delay rate and initial delay estimation are:

50 masec resolution in a 10 Hz bandwidth with ± 1 amin of range.

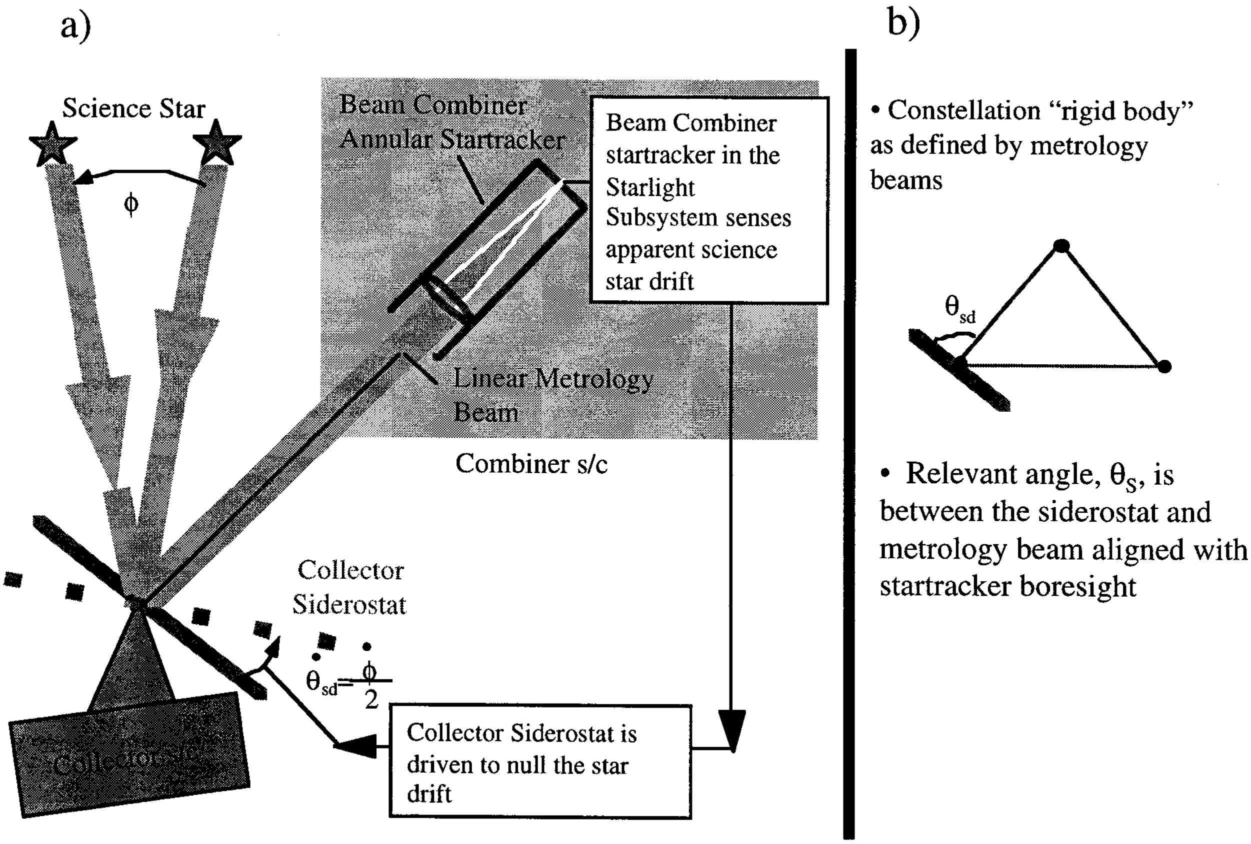


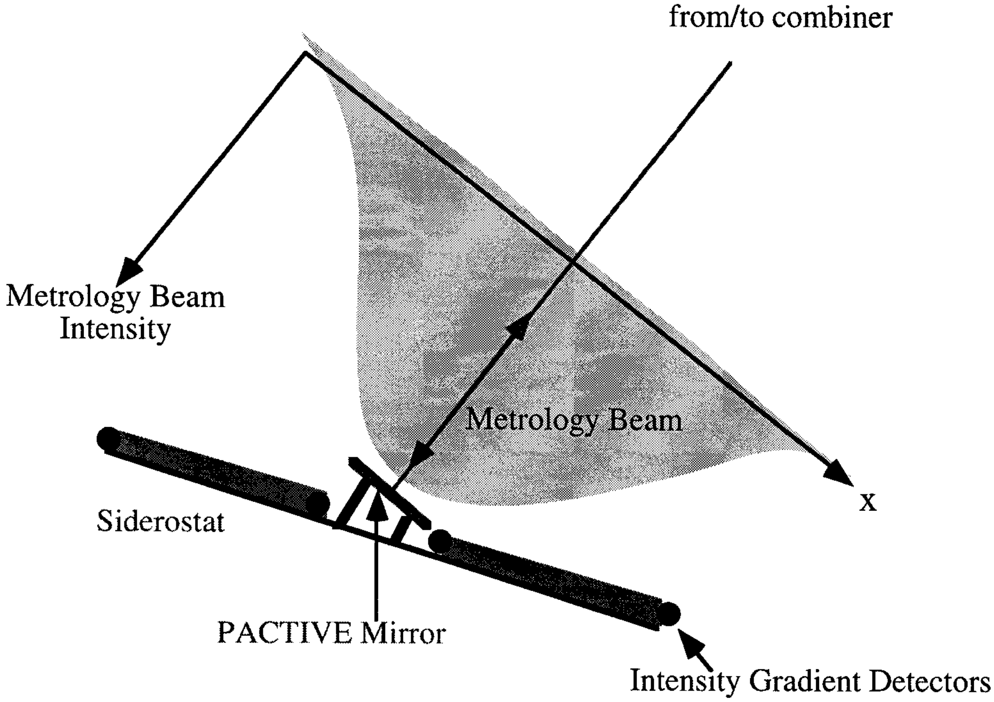
Figure 4.1.

Implementation of Angular Metrology: PACTIVE metrology concept

The function of the metrology subsystem in the concept described in Figure 4.1.a is to measure the angle θ_{sd} defined in Fig 4.1.b.

In a typical implementation, a heterodyne interferometer metrology system uses a cornercube retroreflectorat the target to make the system insensitive to orientation of the target. In this case, however, it is precisely the orientation of the target (siderostat) that we want to measure. Therefore, instead of the retroreflector we plan to use a flat mirror actively articulated in angle relative to the siderostat.

The proposed configuration is shown in Fig. 4.2. A metrology beam inserted in the starlight path by the beam launcher and pointed by the Fast Steering Mirror (FSM) in each arm of the beam combiner on the combiner spacecraft arrives at the collector and is reflected by the flat PACTIVE[c] mirror. First, the FSM must point the metrology beam so that it is centered on the PACTIVE mirror and then PACTIVE mirror must be actuated to reflect the incident metrology beam back on itself. The angle between the PACTIVE mirror and the siderostat mirror at which the retroreflection is achieved will give us the siderostat angle, θ_{sd}.



$$\theta_{sd} = (\text{Angle of PACTIVE Mirror relative to Siderostat}) + 90^\circ$$

Figure 4.2. PACTIVE concept. Intensity gradient detectors are used to center the incident metrology beam and an articulated mirror reflects it back on itself. The angle between the siderostat and PACTIVE mirror required to achieve retroreflection is the desired quantity..

To implement this we need a pointing sensors on the collector that will control the pointing of the fast steering mirror. A currently baselined approach is to use a suite of intensity gradient detectors. These are discrete photodetectors distributed across the siderostat in two orthogonal directions (tip and tilt). The intensity gradient between the corresponding pairs is the error signal for beam de-center. The outer pairs will be used for coarse acquisition of the metrology beam and the inner pairs for fine pointing. The beam parameters of the incident Gaussian beam are given in Table 2.1.

The current performance requirement on this sensor is 50 masec in a 10 Hz bandwidth.

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[c] Term PACTIVE is used for "historical" reasons. In the past we have explored an active metrology option in which a retroreflector is replaced with an optical transponder: a laser phase-locked to the incoming beam and steered back along the incoming beam. In the current scheme, the "ACTIVE" part refers to the active pointing and "P" in front refers to passive reflection, i.e. no laser at reflector.

The fundamental sensitivity of the system is limited by dark current noise in the photodetectors (P_d) and is scaled by the location of the photodetectors relative to the center of PACTIVE mirror (r_{PD}) and the diameter of the photodetector's active area (D_{PD}). We have evaluated the sensitivity of the system baselined with the following parameters:

Table 4.1. Parameters used in the evaluation of the intensity gradient detector sensitivity.

Parameter		Value	Comments
Photodetector type		InGaAs	Fermionics Opto-Technology, FD3000W
Dark noise power	P_d	23 nW	
Detector diameter	D	3 mm	
Gaussian beam radius at collector			
at 1 km	w	63 mm	
at 100 m	w	9.1 mm	
Location of inside pair (distance between PD and center)	r_{PD}	12mm	Chosen to clear PACTIVE mirror. Gap between PACTIVE mirror and siderostat is a convenient location.

To achieve 50 masec resolution at 1 km (0.24 mm de-center) the total power in the metrology beam launched toward the collector must be greater than 5 mW. At 100 m the power requirement is actually greater (37 mW), because the photodetectors see only the tails of the now small Gaussian beam. Both of these numbers, however, are acceptable as we are planning to use 200 mW Nd:YAG lasers[7] and should be able to launch about 50 mW out of the beam launcher. Another potential limitation on the resolution of this sensor is the uniformity of the actual intensity distribution. This issue is being investigated.

Once the incoming metrology beam is centered on the PACTIVE mirror on the collector, the PACTIVE mirror must be actuated to reflect the metrology beam back on itself. This requires a pointing sensor on the combiner. On the combiner intensity gradient detectors will be used for coarse acquisition only, because the returned power (25 dB round trip loss) is too low for intensity gradient detectors to achieve 50 masec resolution. Consequently, the primary sensor on the combiner will be a phase gradient detector.

Phase gradient detector senses a tilt in the phase front of the returning beam. Figure 4.3 illustrates the concept in one dimension. Two collimated optical beams are brought together on two separated photodetectors PD1 and PD2, most likely segments of a quad-cell. Each of these photodetectors will generate the same heterodyne beat, but with a different phase. The phase difference, ϕ_{PD1}- ϕ_{PD2}, is proportional to the angle between the propagation directions of the two beams.

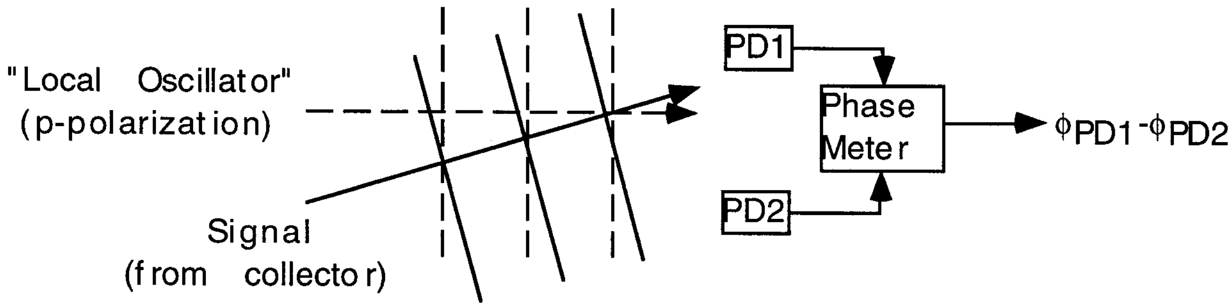

Figure 4.3. Phase gradient detector concept.

The phase gradient detectors cannot be used without the intensity gradient detectors, because the acquisition range of phase gradient detectors is limited to ~(wavelength / beam diameter)=λ/D_o=0.2 amin versus required +/- 1 amin. These detectors therefore will be used as fine pointing sensors once the intensity gradient detectors on the combiner have acquired and coarsely pointed the beam reflected by the PACTIVE mirror. Once the two beams have been aligned to required tolerances, phase from any one detector, or an average phase from all detectors, can be used as the range related phase for linear metrology. It should be pointed out that the phase gradient detector is immune to self-interference, as self-interference contribution appears common mode on all detectors. Of course, any range-related phase combination is still impacted by self-interference and self-interference suppression techniques must be used.

Fig. 4.4 shows one complete metrology leg between combiner and one of the collector spacecraft. An identical system operates between the combiner and the other collector. Metrology beam is inserted by the beam launcher into the starlight path[3] and is directed by the fast-steering mirror towards the center of PACTIVE mirror on the collector. The error signal in this pointing loop is provided by the intensity gradient detectors on collectors and the loop is closed via an interspacecraft RF uplink to the combiner.

The PACTIVE mirror pointing is controlled by a combination of intensity gradient and phase gradient detectors on the combiner. The loop is gain closed via a RF downlink to the collector.

Once both of the above loops are closed, the encoders on the PACTIVE mirror will provide the tip and tilt of the PACTIVE mirror relative to the siderostat, θ_{sd}, see Fig. 4.2. Angle θ_{sd} together with the information from the triangle survey is then used to determine the baseline angle θ, see Fig. 2.1 .

Constellation Survey

To solve for external delay, constellation triangle formed by the three optical fiducial points, Fig. 2.1, must be surveyed. This can be accomplished in a number of ways. One would be to measure all three sides of the triangle with absolute metrology. Another is to measure the combination of triangle angles and the baseline. The latter is currently planned, because we already have the angular metrology and the AFF will provide sufficient absolute baseline knowledge.

The triangle is measured by adding a third leg of PACTIVE metrology running between the two collector spacecraft. The configuration is identical to what is shown in Fig. 4.4 except that there are no starlight components.

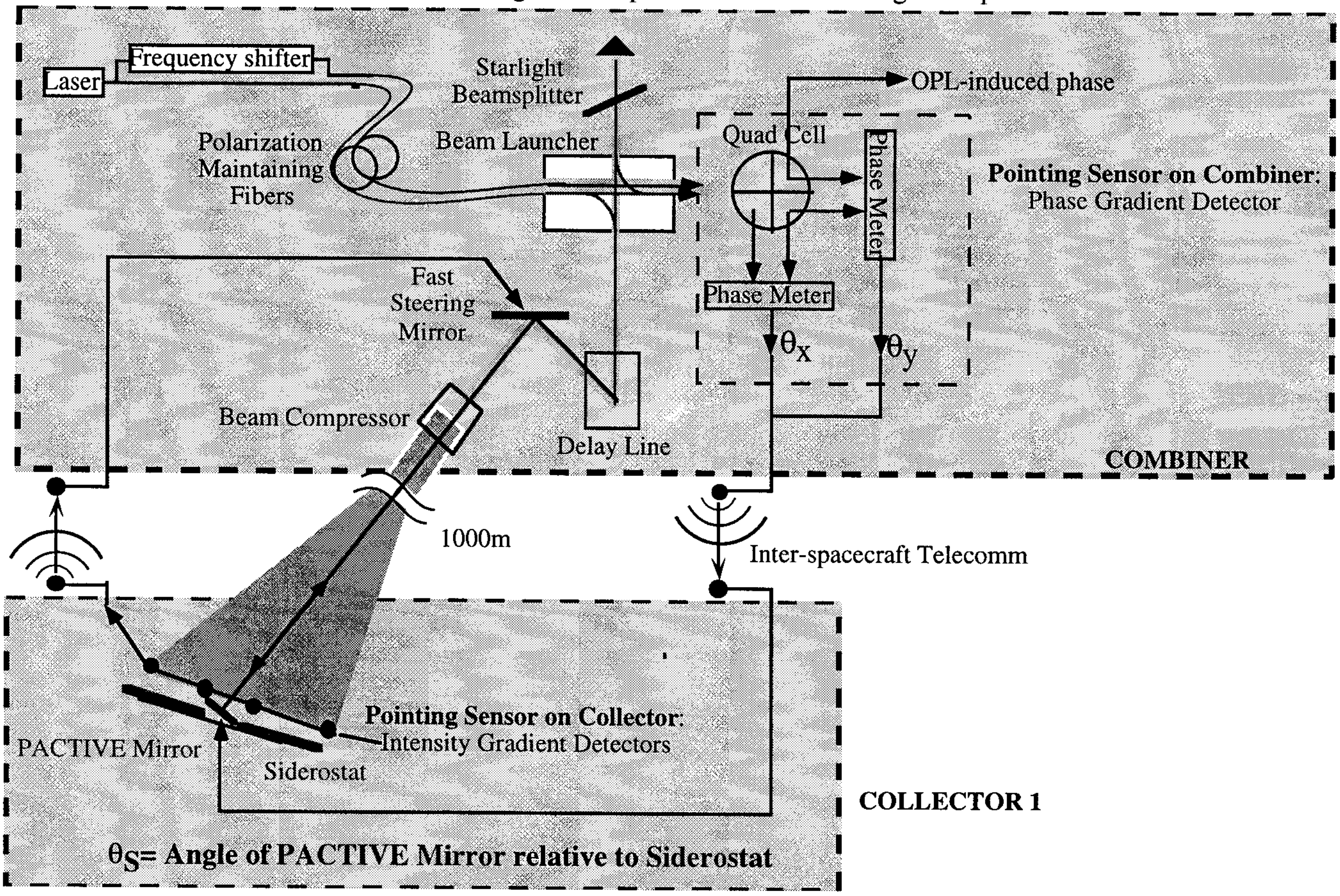

Figure 4.4. One leg of a PACTIVE metrology between the combiner and one of the collectors. An identical system exists between the combiner and another collector and a similar system operates between the two collectors

5. SUMMARY

The Deep Space 3 metrology subsystem provides two measurement capabilities: relative linear metrology and angular metrology.

The linear metrology implementation is based on a heterodyne interferometer laser gauge. Long interspacecraft separations (1 km) and restriction of the metrology aperture to 2 cm result in a very high optical power loss (25 dB). The usual heterodyne interferometer would be inoperable with this level of power loss because magnitude of self-interference, a performance limiting pseudo-noise source, would become comparable to the useful range-related signal. In this paper we presented a concept of frequency modulated metrology designed to overcome this obstacle.

Angular metrology is necessary to determine the initial stellar fringe delay and subsequent delay rate. This information is necessary to keep the fringe search time within practical limits. Angular sensitivity is introduced into the metrology system by using as a target reflector an articulated flat mirror mounted on the target surface .

6. ACKNOWLEDGEMENTS

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